Aalto University
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Master's Programme in ICT Innovation

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An Arm-Assistive Medical Device using Soft Robotics Technology

Master's Thesis
Espoo, August 5, 2015

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ABSTRACT OF MASTER'S THESIS

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With the emergence of world population aging, the health issues of elderly people attract increasing people's attention. As many elderly people are suffering from the limitation of shoulder and arm functions, it is necessary to develop medical devices which provide strength supports for the elder people. With this motivation, we intended to develop a wearable soft robotics solution which provides extra strength to arm function of the elderly users.

This thesis gives an academic view of the development project and tries to gain insights on user intention detection, sensing and control technology, including sensor selection, signal filtering and data fusion etc. This thesis work focuses on the development process of detecting the intention of user's movement and providing the supporting force according to user's requirements, and using the control technology to control the force.

Instead of using rigid materials, we applied soft materials and organic structures, which makes the device lightweight, cost-effective and comfortable. We used commercial off-the-shelf components to develop the system which reduced the development time and increased the stability and flexibility of the system.

The prototype of this product was sent to a research center for safety and user evaluation. The evaluation shows that the device can help the user lifting his/her arm as well as do some basic operations, such as eating or drinking. Most of the testers were satisfied with the functionality of the prototype and showed great interest in the product.

Keywords:	Soft Robotics, Wearable Technology, Arm-Assistive Medical Device, Commercial off-the-shelf Technology, Force Control, Sensing Technology
Language:	English

Foreword

First of all, I would like to thank Prof. Heikki Saikkonen and Dr. Vesa Hirvisalo, my supervisor and instructor at Aalto University, for their patient guidance and helpful advices during the whole thesis work.

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Finally, I want to thank my family and friends, for their supports during my study in Finland and Sweden!

Espoo, August 5, 2015

Shilei He

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The technical contribution that this thesis describes was done during an industrial internship in Bioservo Technologies AB, Sweden. All intellectual property generated during the internship is owned by Bioservo Technologies. For further information and contact, refer to www.bioservo.com.

Abbreviations and Acronyms

IMU	Inertial Measurement Unit
TLC	Tendon Load Cell
RPM	Revolution(s) Per Minute
p-ADL	Personal Activities of Daily Living
COTS	Commercial off the Shelf
IDE	Integrated Development Environment
DOF	Degree of the Freedom
MEMS	Micro-electro-mechanical systems
PID Controller	Proportional-integral-derivative Controller
ADC	Analog-to-digital Converter
PWM	Pulse Width Modulation
GPIO	General Purpose Input Output
RC	Radio Control
I2C	Inter-Integrated Circuit
SPI	Serial Peripheral Interface

Contents

Chapter 1

Introduction

With the emergence of world population aging, the health issues of elderly people attract increasing people's attention. The incidence of disability increases with people's age which has a major impact on elderly's life. Hence, products or devices assisting the elderly with their activities of daily life (ADL) are essential. With the purpose of helping people with reduced arm muscle strength lifting their arm, Bioservo Technologies AB is organising a development project, which focuses on wearable, assistive medical devices using soft robotics technology. This thesis gives an academic view of the contribution done by the author of this thesis in the development project, the methods and materials used, and the related background information.

1.1 Motivation

Many elderly people with disabilities want to remain living in their homes. However, with the increasing of the age, many of them will experience the disability of shoulder and arm functions. According to the clinical study [21] in London 2013, shoulder abduction showed a significant decline averaging 5 degrees/decade in men and 6 degrees/decade in women; and these number increased to 0.80 degrees/year starting at the age of 71 years for men, and 0.74 degrees/year for women starting at 63 years. When there is a limitation for people to lift their arm over 100 degrees, some basic functions cannot be performed [22] and 70% of disabled people said that, due to losing care and support services, they were sometimes unable to wash, dress or eat [27].

As many elderly people are suffering from the limitation of shoulder and arm functions, it is necessary to develop a medical device which provides strength supports for the elder people. With this motivation, we intended to produce a soft robotics solution that provides extra strength to arm function of the elderly users.

1.2 Problem and Scope

The aim of this project is to develop a wearable medical solution which provides extra strength to the arm function of elderly users during their personal activities of daily life (p-ADL), and the solution is implemented using soft robotics technology. This thesis work focuses on the electronics and software aspects and tries to gain insights on the following questions:

- How to detect the intention of user's movement and transfer it to force signal?
- How to provide the supporting force according to user's needs?
- What method can be used to control the force signal?

First, in order to provide the suitable force support for the user, we should analyse user's demand of the support which can be implemented by detecting user's intention and transferring it to the corresponding force. Then, supporting force should be provided according to user's needs which helps the user lifting the arm. Furthermore, it is necessary to implement the force control of the system to increase the safety and accuracy.

This thesis will cover the three questions above and describes the details of sensor selection, signal filtering, data fusion, interface and communication of components, integration of the system and user testing.

The target Group of this product is elderly people or the people with reduced force strength on the arm. Therefore, there are some factors should be considered. First, the product should be easy to use and control by the user himself/herself. Second, the supporting force should be adjustable according to different needs of users. Finally, the product should has high safety and be able to stop at the emergency time.

1.3 Results

In this thesis work, a prototype has been created to evaluate the viability of the approach. The electronics and software part of the prototype has been done by the author of the thesis, including the system requirements analysis, sensor selection, components installation, coding and testing. The components of the prototype have been evaluated separately before the integration, and the prototype of this product has been sent to a research center for safety and user testing. The device fulfilled the safety requirements and we obtained a good result from the testers.

The testers were the people with reduced force strength in the arm and the result shows that the device can help the user lifting the arm to do some basic operations, such as eating and drinking. Some testers was excited that they could lifting the arm again. Most of the testers were satisfied with the functionality of the prototype and showed great interest in the product.

1.4 Structure of the Thesis

Chapter 2 analyses the human arm disabilities as well as the the user demands of the arm-assistive device. It briefly introduces the background of the soft robotics technology and the wearable technology. The state of the art of the arm-assistive device has been analysed for improving the product development and avoiding the infringing patents.

Chapter 3 describes the wearable soft robotics technology which is intended to be widely implemented in medical devices. It also introduces the Commercial off-the-shelf Technology which is implemented in this thesis work to reduce the development time as well as increasing the flexibility of the product. Additionally, it indicates the hardware and software platform applied in this thesis work.

Chapter 4 illustrates the methods implemented in this thesis work in details. It analyses the motion of the human arm and introduces the methods that used to detect user's motion as well as the force control technology, including the components and algorithms that are selected to control the system.

In Chapter 5, the system design of the arm-assistive device has been introduced. It analyses the requirements of the system, and shows the details of the system architecture, including sensing unit, control unit, actuating unit and control panel.

Chapter 6 describes a prototype of the arm-assistive device, including the implementation of each unit as well as the integration of the system. It indicates the types, electronic characterises and functions of the selected components as well as the application method of the components.

In Chapter 7, the system evaluation and the result have been shown in details. It describes the setup of the evaluation and analyses the performance and the functionality of the system. The room for improvement has also been discussed in this chapter.

Chapter 8 draws a conclusion of the thesis work.

Chapter 2

Background

Many people are suffering from the sickness of arm function, such as stroke, therefore, it is necessary to develop a solution to provide force support for them. Using robotics technology could be the primary method to implement the solution. In present, the research of the robotics has been influenced by the biology field. Instead of rigid materials, the trend of the robotics is now towards the use of soft, pliable organic structures, materials, and surfaces [6]. As the soft robotics technology is a new area, there are more research materials than the textbooks. The materials could be found in *Soft Robotics: Transferring Theory to Application* [6] and *Soft Computing in Advanced Robotics* [5].

2.1 Human Arm Disabilities

Shoulder or arm problems occur frequently in older adults, such as frozen shoulder, hemiparesis and stroke. Many of the older people suffer from the pain in the arm when reaching high, and some of them even lose the ability of arm function. Strokes affect over 795,000 people annually in the United States and 15 million worldwide. This disabling condition could result in paralysis of upper and/or lower limbs [24]. Many patients have to receive the treatment regularly by a dedicated physical therapist. However, strokes are difficult to remedy and need the patients to visit the rehabilitation clinic frequently. Moreover, the payment of the treatment is expensive and it takes a long time to be fully recovered. Therefore, lightweight and wearable devices are necessary to provide the strength support for elderly or people with problems in arm. The device should also be cost-effective and easy to use.

2.2 Soft Robotics Technology

The term “soft robotics” has been deliberately coined by this emerging field of research to describe soft, organic embodiments with biologically-inspired sensors and knowledge processing combined with intuitive, safe and more sensitive interaction. Instead of implementing the rigid mechanical structures of the past, a new robotics paradigm is now starting to focus on soft, pliable, sensitive, organic representations - on “soft robotics” [6]. The materials are designed to be soft and resilient to perform some complex movements. Electronics, software and materials should be integrated effectively to achieve high level functions.

The soft robotics technology can be used in medical field to help people with problems on walking and arm function etc. For example, Conor Walsh from Harvard University designed a robotic exosuit which is a soft textile garment used to enhance a human’s natural mobility [34]. It can be used to improve the endurance of soldiers as well as used on patients with motor impairments.

With the research of the robotics technology, soft robotics show significantly potential usage in many field, such as medical, electronics and aviation industry. Many research centers focus on the study of soft robotics technology. For example, Researchers at MIT’s Computer Science and Artificial Intelligence Lab (CSAIL) have come up with a single 3D printed, soft-shelled tentacle that is designed to navigate through all manner of pipes, channels, and burrows using rubber. Unlike traditional robots, these rubber robots do not have fixed-joints. Instead, this soft-shelled automaton is constructed with a group of hollow, individually inflatable channels ranged down either side of it that, when filled with air, change shape and bend that part of the arm in the required direction [14]. West Lafayette from Purdue University also shows a technology which can be used to develop soft robots - inkjet-printing technology. It shows the possibility for mass-produce electronic circuits made of liquid-metal alloys for “soft robots” and flexible electronics [32].

2.3 Wearable Technology

The terms “wearable technology”, “wearable devices”, and “wearables” all refer to electronic technologies or computers that are incorporated into items of clothing and accessories which can comfortably be worn on the body [19]. Nowadays, wearable technology are widely used in health care industries and will have a big share in electronics market as well as data collection market. Moreover, wearable technology may provide an integral part of the solution for providing health care to a growing world population that will be strained by a ballooning aging population [26].

The most popular devices using wearable technology could be smart watches and web-enabled glasses. These products applied sensors to detect the environment around or the state of the customer, for example the heart rate of the user. Moreover, the user can access the data hands-free from networks and monitor or record the data through the device.

There is a trend of combination of wearable technology and robotics, called "wearable robotics". It is a technology that designed to aid human movement with light and efficient mechanical materials or electronics, and built into the fabric of clothes [34]. It has been designed to be used on the patients with movement problems and should be more comfortable and lightweight.

2.4 State of the Art

With the increasing requirements of the arm assisting products, much research has been conducted in recent years. Some of them are commercialized and available in the market. However, most devices are heavy, conspicuous and unwearable which are not convenient to be used in personal activities of daily life. Hence, a research of existing arm-support technologies is necessary for improving the development process and also avoiding infringing patents.

Darwing [3] from FOCAL Meditech BV is a dynamic arm support device which is developed for people with very limited muscle strength or even without any arm function. It has been divided into two parts, a fore arm and an upper arm. Movements by the fore arm are independent from the movements of the upper arm, therefore they do not interfere with each other and provides more natural performance. Another advantage of Darwing is the supported force can be adjusted by the user himself. For example, when the user need to hold a heavy object, the supported force can be easily adjusted. Furthermore, the recurring activities can be stored in the memory so that the user could preform some basic movements like eating or drinking by just pressing a button. However, there are some inadequates. First, this device can not work autonomously, it should be mounted to the wheelchair and it performs like an extra arm instead of supporting the arm. Second, it is heavy, bulky and uncomfortable as it is made up of metal and some hard plastics. Hence, this type of devices can provide robust strength but has a very limited group of user.

Armon Edero [2] provides a commercial solution for the arm support without using the actuator. It compensates the weight of user's arm by a spring compensation system. It is not only suitable for people with diseases in their arms, but also useful for some static professional groups or activities, such as office work, dentistry and laboratory. However, it is difficult for Armon Edero to provide the accuracy force to meet user's requirement, because it has not the sensing system which detects the exactly demands of user. Furthermore, the device should be set on the table or wheelchair which lacks of mobility.

Another type of arm support solution is exoskeleton arm, for example ZJUESA from China 2012. ZJUESA [35] is made by rigid materials with three cuffs on upper arm, forearm and wrist. It is wearable and provides the movements of 6 degree of freedom (DOF), 3 DOF each for shoulder and wrist including flexion/extension, abduction/adduction and rotation. Specially, flexion and extension are implemented by crank-slide mechanism composed of a cylinder and links. Pressure sensors and position sensors are utilized to provide the feedback of pressure and regular displacements for movement calculation. Actuators are implemented for driving the exoskeleton arm. However, this exoskeleton arm is bulky, conspicuous and lack of comfort which is not suitable for daily use.

As most of the arm-support solutions can not work autonomously or rely on rigid elements which are bulky and conspicuous, increasingly research focus on wearable devices using soft robotics technology. A wearable active upper body soft orthotic system has been proposed in Portugal on 2012 [24]. This system consists of a fabric garment including a shoulder brace and a elbow brace, and two cable-driven series elastic actuators providing assistive forces. Inertial Measurement Units (IMUs) and position sensors are implemented to monitor user's posture and the position of the actuator as the feedback of the control unit. Avoiding rigid elements improves the safety of the device and applies the device light weight which is easier for daily wearing. However, using two actuators makes the system complex and energy consuming. Moreover, this device can only provide the force support on abduction and adduction DOF now which has a limitation of the usage.

Chapter 3

COTS Technology for Wearable Soft Robotics

This chapter describes the wearable soft robotics technology which intended to be widely implemented in medical devices to help people with problems of motor impairments. It also introduces the Commercial off-the-shelf Technology which is used in this thesis work to reduce the development time as well as increasing the flexibility of the product. Additionally, it indicates the hardware and software platform applied in this thesis work.

3.1 Wearable Soft Robotic

Humans are dream of to become strong and agile, and researchers have spent countless hours and resources to achieve it. One of the method could be using wearable assistive devices. As the vast majority of the devices are rigid exoskeletons, which are heavy and bulky, there is a trend to develop wearable devices using soft robotics technology.

Alan T. Asbeck [13] from Harvard university launched a soft exosuit solution for hip assistance. It can be applied on individuals with the needs of carrying heavy loads such as soldiers to reduce muscle fatigue, metabolic expenditure, or injury rates, as well as applied on people needing assistance with walking, such as the elderly or patients with mobility problem. Instead of using rigid load-bearing structures, it implements the soft robotics technology by using fabric materials to make it easy to wear and comfortable. Due to its soft design, the system is light and does not restrict the motion of the hip in the ab- or adduction directions or rotation about the leg axis. In addition, donning and doffing of the device are easy and can be rapid, and the device is simply to be disengaged from the wearer while the assistance is not required.

The wearable soft robotics technology could be used in medical field, such as human rehabilitation and assistance. An active soft orthotic device [25] has been designed and prototyped for ankle-foot rehabilitation. The device implemented four pneumatic artificial muscles assisting dorsiflexion and plantarflexion as well as inversion and eversion. It mimicked the muscle-tendon-ligament-skin architecture in the biological musculoskeletal system of the human ankle. Furthermore, it applied wearable and soft materials including soft actuators and sensors. The soft structure of the device is the key feature that provides active assistance without restricting natural degrees of freedom at the ankle joint. As a result, the prototype shows the ability of generating an ankle range of motion of 27 degrees which indicates a rich space for the wearable soft robot technologies in the future.

In addition, TREMOR neurorobot [15] provides a solution for patients with tremor using wearable soft robotics technology, and it has been developed for Tremor assessment and suppression. The TREMOR neurorobot monitors the whole neuromusculoskeletal system which characterizes both voluntary movement and tremor, and then stimulates upper limb muscles to compensate functionally for the tremor. It has been implemented using soft robot interfaces which satisfies users' aesthetic and cosmetic preferences.

3.2 Commercial off-the-shelf Technology

Commercial off-the-shelf (COTS) [10] technology are used for developing products using ready-made software or hardware and available for sale to the general public. Commercial off-the-shelf systems are popular in many fields due to their rich feature sets, ease of use, and cost effectiveness [4]. Moreover, this technology has the advantage of reducing development time, shortening design-to-production cycles and increasing the flexibility of the product.

Commercial off-the-shelf technology has been applied in robotics field for some years. CotsBots [16], distributed mobile robots designed by Sarah Bergbreiter and K.S.J. Pister from Berkeley sensor and actuator center in USA, are built entirely from commercial off-the-shelf components. Each of the pieces comprising the CotsBots are commercially available with minimal assembly required. As the hardware is purchased off-the-shelf, the CotsBots are small, inexpensive, and provide a simple and extremely flexible hardware and software platform for the user.

Commercial off-the-shelf technology has been widely used in product development. It reduces the development time and costs less than the traditional development process. Using this technology, we can implement the system with cheaper hardware, such as ready-made microcontroller and sensors. In this thesis work, we implemented the system using commercial off-the-shelf hardware. For example, we used STM32F401 discovery board as the main board which is inexpensive and easy to use, and only very simple modifications are necessary. We also applied some commercial off-the-shelf sensors, for example the ready-made breakout board sensors which are flexible and simple to program. Additionally, using commercial off-the-shelf components increases the stability of the system. The ready-made components only need simple modifications and easy to apply which increases the stability of the system.

3.3 Microcontroller

In this thesis work, we implemented the system using some commercial off-the-shelf hardware. For example, Discovery board STM32F401 was used in this thesis work as the main board. It is a ready-made microcontroller and provides powerful hardware functions, multiple interfaces as well as a easy-to-use firmware.

3.3.1 Hardware

The hardware platform of the project is STM32f401 discovery board [30] from ST company. This board has a ARM 32-bit CortexTM-M4 RISC core which can be operated at a frequency of up to 84 MHz. The Cortex-M4 core features a single-precision floating point unit (FPU) which supports the complex floating number calculations. The board also has a flash memory up to 256 Kbytes and a SRAM up to 64 Kbytes. It can be powered through a USB port or an external power supply of 5 Volts. It has multiple I/O ports, eight LEDs and two push buttons which are convenient to use. Moreover, it features with a user USB port which can communicate with computer or other devices. The board is shown in Figure 3.1.

3.3.2 Software

The software environment of this project is Windows PC 7. It is equipped with an Integrated Development Environment (IDE), a debug tool and a powerful firmware. A mathematics tool - labview was installed to communicate between the computer and the STM32F401-discovery board, the computer

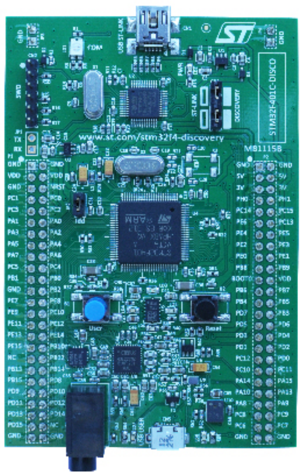

Figure 3.1: STM32F401-Discovery Board [30]

can monitor the board by reading the data from the board and recording for data analysis, it can also send the data to the board to set values.

3.3.2.1 Integrated Development Environment

The supported IDEs of STM32F401 board are EWARM (IAR Embedded Workbench), MDK-ARMTM^{TM} and Atollic TrueSTUDIO. MDK-ARM^{TM} has been chosen for this project as it has powerful debug functions and a free evaluation version. The code can be download through USB port which is convenient.

3.3.2.2 Firmware

This project is based on a firmware provided by ST company. This firmware has a variety of libraries and examples for peripherals, such as STM32 USB device library which is provided for the USB devices. Moreover, it provides pre-configured project templates for users, and third party libraries are also acceptable to use. Figure 3.2 shows the content of the firmware.

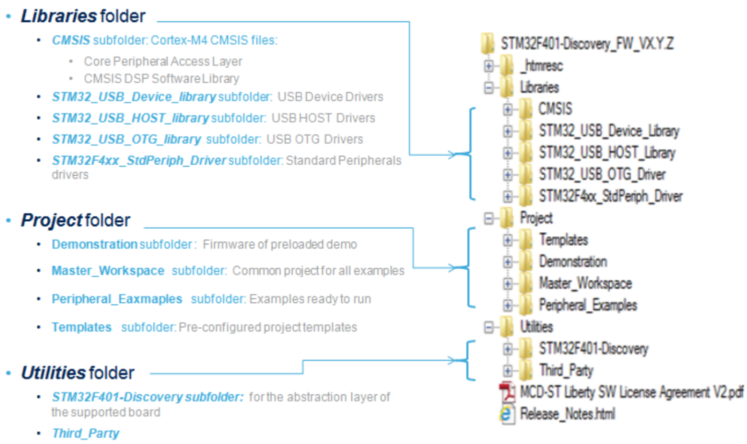

Figure 3.2: STM32F401-Discovery Board [29]

Chapter 4

Assisting Human Arm Motions

This chapter describes the related physics and control methodology which are used in the implementation of the electronics and software part of the arm support system. It analyses the motion of the human arm which indicates the relationship between the lifting angle and the required force to support user's arm. In addition, it introduces the methods used to detect user's intention as well as the force control technology including the components and algorithms which are selected to control the system.

4.1 Motion of the Human Arm

In order to provide the force support for user's arm, we should analyse the movement of the human arm. The angle between the arm and the body increases with the lifting of the arm, so that we can find the relationship between the required force and the lifting angle, and offer the corresponding force for the motion of the arm. Figure 4.1 shows the relationship between the required force and the lifting angle of the arm.

Then, we can build the mathematics model, shown in Figure 4.2.

According to Figure 4.2, we obtain the relationship between the required force F and the lifting angle of the arm θ:

$$F * L_1 = mg * L_2 * sin\theta$$

where L1: height of the shoulder padding,
L2: 1/2 of the arm length,
mg: gravity of the arm.

Therefore,

$$F = \frac{mg * L_2}{L_1} * sin\theta = K * sin\theta$$

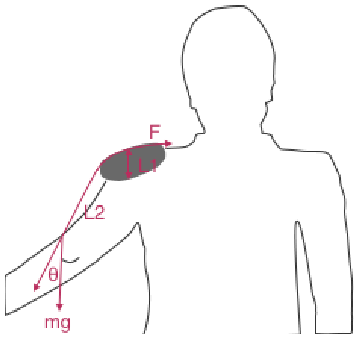

Figure 4.1: Angle-Force Relationship

We can see F is proportional to $sin\theta$, and the coefficient K is different for different size of people as the gravity and the length of people's arms are different. Moreover, people has different feelings and situations, therefore the requirements of the force support are also different, which increases the difficulty of the research. Nevertheless, user intention analysis is helpful to estimate the force-angle relationship. We can implement this by testing on different size of people and adjusting the value based on people's feelings. In addition, the coefficient K is designed to be adjustable by the users which improves the flexibility of the device.

4.2 Sensing based on Inertial Measurements

As there is a relationship between the required force and the lifting angle of the arm, we can decide the force by measuring the lifting angle. This can be implemented by using an 6-DOF IMU, which consists of a 3-axis accelerometer and a 3-axis gyroscope. Data fusion and filtering of the signals should be implemented for the sensors. Monitoring of the force signal can also be implemented using tendon load cells which detect the actual force.

4.2.1 Inertial Measurement Unit

An Inertial Measurement Unit (IMU) is a self-contained system that measures linear and angular motion usually with a triad of accelerometer and a triad of gyroscope, sometimes also a magnetometer [33]. It is widely used

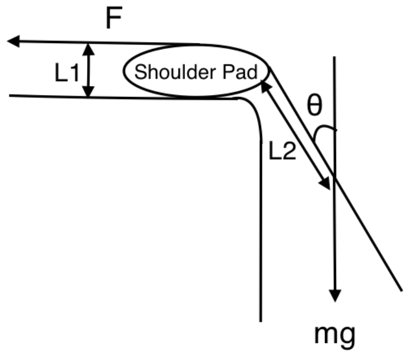

Figure 4.2: Mathematics Model of Angle-Force Relationship

in aircraft, spacecraft and watercraft for position and orientation detection, or motion monitoring and compensation. Meanwhile, in some applications, where the net acceleration or force on a system over time is gravity, an IMU can also be used to measure the static angle of tilt or inclination [8]. As the trend of miniaturization of electronic products, micro-electro-mechanical systems (MEMS) technology has been wildly used in the production of IMUs. This technology has the advantage of sensitivity, stability, small size and low power consumption. Hence, a MEMS IMU is selected as the best choice to monitor the movement of user's arm in this project.

An IMU can be classified by its degrees of freedom (DOF). For example, a 6-DOF device could be a 3-axis accelerometer (3 DOFs) combined with a 3-axis gyroscope (3 DOFs). In this thesis, a 6-DOF IMU was used to measure the lift angle of user's upper-arm.

4.2.1.1 Accelerometer

An accelerometer is a device that measures proper acceleration or g-force which is different as coordinate acceleration. In relativity theory, proper acceleration is the physical acceleration (such as measurable acceleration) experienced by an object [31]. In other words, an accelerometer detects the acceleration which is caused by gravitational, also known as g-acceleration or g-force.

An 3-axis accelerometer measures three g-acceleration values in a world coordinate system with three axis (X, Y, Z), shown in Figure 4.3 (a). Let A_x, A_y, A_z be the output of tri-axial accelerations. Then the vector of the acceleration could be $\vec{A}$, which equals to $A_x\vec{X} + A_y\vec{Y} + A_z\vec{Z}$. Following shows

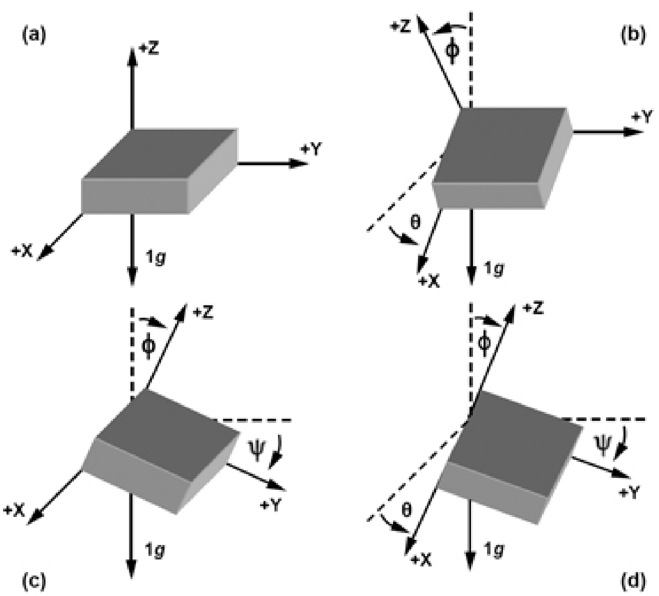

Figure 4.3: Angles for independent Inclination Sensing [8]

the general working process of the accelerometer.

First of all, In order to calculate the angle of inclination, given the assumption that gravity is the only stimulus associated with the acceleration. Then, the inclination sensing can be implemented using an accelerometer by comparing the vector quantities of g-acceleration with the values from a reference position. If we take the typical orientation of a device as the reference position which the x and y axis are in the plane of the horizon (0 g field) and the z axis is orthogonal to the horizon (1 g field), shown in Figure 4.3 (a), we can obtain the angle between the horizon and the x-axis of the accelerometer, shown as θ, the angle between the horizon and the y-axis of the accelerometer, shown as ψ and the angle between the gravity vector and the z-axis of the accelerometer, shown as ϕ. According to the basic trigonometry, the angles of inclination can be calculated as:

$$\theta = tan^{-1}\frac{A_x}{\sqrt{{A_y}^2 + {A_z}^2}}$$

$$\psi = tan^{-1}\frac{A_y}{\sqrt{{A_x}^2 + {A_z}^2}}$$

$$\phi = tan^{-1}\frac{\sqrt{{A_x}^2 + {A_y}^2}}{A_z}$$

When in the initial position that A_x and A_y are 0 g, and A_z equals to 1 g, all calculated angles would be 0.

However, in this thesis work, the accelerometer should be placed vertically as the initial position because user's arm should be release and in parallel to the body and the IMU should be stickied on user's arm. Therefore, the reference position should be 0 g on the y- and z-axes and 1 g on the x-axis. See the mathematics model shown in Figure 4.4 where A is the vector of the acceleration.

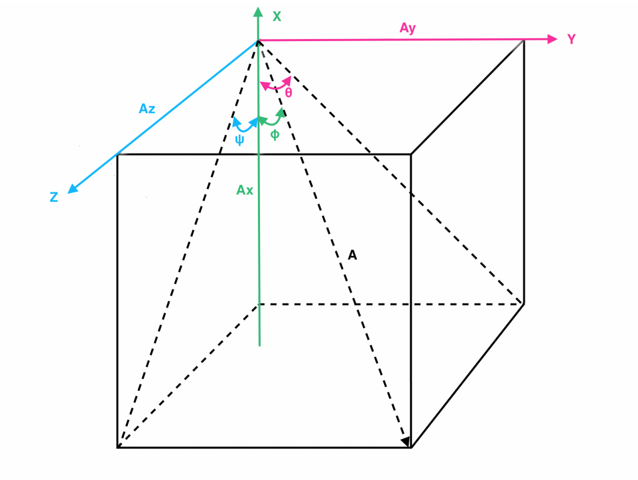

Figure 4.4: Mathematics modeling of angle calculation

In order to analyse the movement of user's arm, it is necessary to do the decomposition of the movement. The angle between the projection of vector A on XY plane and gravity θ can be calculated as:

$$\theta = tan^{-1}\frac{A_y}{\sqrt{{A_x}^2}}$$

Similarly, the angle between the projection of vector A on XZ plane and gravity ψ can be calculated as:

$$\psi = tan^{-1}\frac{A_z}{\sqrt{{A_x}^2}}$$

And the angle between the vector A and gravity ϕ could be calculated as

$$\phi = tan^{-1}\frac{\sqrt{{A_y}^2 + {A_z}^2}}{A_x}$$

Comparing the angle ϕ with angle θ and ψ, we can obtain the following relationship:

$$\phi = tan^{-1}\sqrt{tan^2\theta + tan^2\psi}$$

where angle θ and ψ are the raw angles of the movement of abduction/adduction and flexion/extension which will be combined with the rotation values from gyroscope for accuracy result, and the angle ϕ after the combination with gyroscope will be used to decide the reference force to support user's arm.

The calculations above are all based on the ideal situation. However, in real life, the initial position of the accelerometer could not be exactly 0 g on the y- and z-axes and 1 g on the x-axis. Nevertheless, this problem can be solved by detecting the initial position of the accelerometer as the reference position and implementing the calibration based on it.

Assume the position of accelerometer is $\vec{A_2}$ (A_{x2}, A_{y2}, A_{z2}) and the reference position is $\vec{A_1}$ (A_{x1}, A_{y1}, A_{z1}). According to the mathematics of euclidean vector, the angle between these two positions γ can be calculated as:

$$\gamma = cos^{-1}\frac{\vec{A_1} \cdot \vec{A_2}}{|\vec{A_1}||\vec{A_2}|}$$

However, it is not possible to obtain the directions of these two vectors using the formula above, as it does not show either $\vec{A_1}$ is ahead or behind $\vec{A_2}$. If we change to use the Sine function for the calculation. We can obtain:

$$\gamma = sin^{-1}\frac{|\vec{A_1} \times \vec{A_2}|}{|\vec{A_1}||\vec{A_2}|}$$

which has the same problem that it returns a value between 0 and π and we still do not know the directions of the movement. Nevertheless, if we combine those two formulas and use tangent rule for calculation, we can obtain the angle value from -π to π:

$$\gamma = tan^{-1}\frac{|\vec{A_1} \times \vec{A_2}|}{\vec{A_1} \cdot \vec{A_2}}$$

where

$$|\vec{A_1}\times\vec{A_2}| = \sqrt{(A_{y1}A_{z2} - A_{z1}A_{y2})^2 + (A_{z1}A_{x2} - A_{x1}A_{z2})^2 + (A_{x1}A_{y2} - A_{y1}A_{x2})^2}$$

and

$$\vec{A_1} \cdot \vec{A_2} = A_{x1}A_{x2} + A_{y1}A_{y2} + A_{z1}A_{z2}$$

Hence, the angle between two vectors can be indicated as:

$$\gamma = tan^{-1}\frac{\sqrt{(A_{y1}A_{z2} - A_{z1}A_{y2})^2 + (A_{z1}A_{x2} - A_{x1}A_{z2})^2 + (A_{x1}A_{y2} - A_{y1}A_{x2})^2}}{A_{x1}A_{x2} + A_{y1}A_{y2} + A_{z1}A_{z2}}$$

According to the equation above, The angle between the projection of $\vec{A_2}$ on XY plane and gravity based on the reference position can be calculated as:

$$\theta = tan^{-1}\frac{\sqrt{((A_{x1}A_{y2} - A_{y1}A_{x2})^2}}{A_{x1}A_{x2} + A_{y1}A_{y2}}$$

where A_{z1} and A_{z2} equal to zero.

Similarly, the angle of tilt in XZ plane ψ from (A_{x1},0, A_{z1}) to (A_{x2}, 0, A_{z2}) is:

$$\psi = tan^{-1}\frac{\sqrt{(A_{z1}A_{x2} - A_{x1}A_{z2})^2}}{A_{x1}A_{x2} + A_{z1}A_{z2}}$$

4.2.1.2 Gyroscope

A gyroscope is a spatial mechanism which is generally employed for the study of precessional motion of a rotary body [36]. A 3-DOF gyroscope provides the rotation velocities of 3 axis - yaw, pitch and roll. Gyroscopes are widely required in many electric applications, such as gaming and robotics, and MEMS technology has been broadly implemented in gyroscopes, known as MEMS gyroscope. A MEMS gyroscope has vibrating structure which measures the vibration of the body and can provide the angular velocities of 3 axis. It has excellent performance featuring with easy to use and inexpensive. Hence, a MEMS gyroscope is suitable for our project that can be used to study the movement of user's arm.

4.2.1.3 Data Fusion

Although the angles of tilt can be obtained from an accelerometer, we cannot depend on it alone; because the data is not accuracy. First, accelerometer measures the inertial force, this force is ideally only caused by gravity; however, it may be affected by the motion of the device. Second, even if the accelerometer is in a relatively stable state, it is very sensitive to the vibration and mechanical noise. Hence, we may consider using a gyroscope instead of an accelerometer. Gyroscopes detect the rotation, it is not so sensitive to the linear mechanical motion. However, there is another problem with gyroscope, such as drift, it does not return to zero-rate value when motion stops. Nevertheless, a better estimate of inclination value can be obtained by combine the accelerometer and gyroscope. Additionally, a data filter is also helpful to reduce the noise. The accelerometer data is reliable on the long term change, therefore a low pass filter can be used; the gyroscope data is reliable on the short term change because of the drift on the long term, hence, a high pass filter is useful. Therefore, a filter with low-pass feature on accelerometer and high-pass function on gyroscope could be the best solution.

4.2.1.4 Complementary Filter

Complementary filter is a simple estimation technique which is often used to combine measurements and it is less CPU intensive [11]. As shown in Figure 4.5, which is a first-order complementary filter. It consists of a low-pass filter and a high-pass filter. Assume G(s) is the transfer coefficient of the low-pass filter, then the transfer coefficient of high-pass filter is 1-G(s).

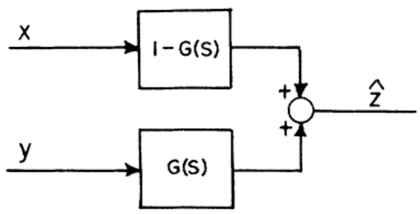

Figure 4.5: Basic complementary filter [11]

According to Figure 4.5, the transfer function can be shown as:

$$Z = (1 - G(S)) * x + G(S) * y$$

where Z: output of the complementary filter,

x, y: input of the complementary filter,
G(S): transfer function of low-pass filter,
1-G(S): transfer function of high-pass filter.

4.2.1.5 Integration of Accelerometer and Gyroscope

The complementary filter provides a best solution for both accelerometer and gyroscope. For the accelerometer, a low-pass filter is implemented which eliminates the affect from external forces and reduces the affect of mechanical noise. The high-pass filter is implemented on the gyroscope which solves the drift problem.

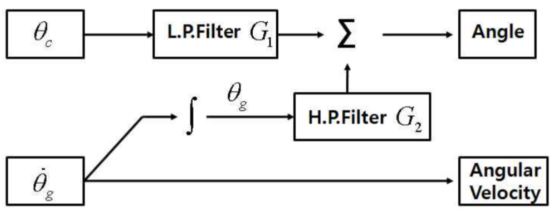

Figure 4.6: The complementary filter for IMU [20]

According to Figure 4.6, the transfer function of the filter can be shown as following:

$$Angle_{n+1} = (1 - G_1) * (Angle_n + gyroRate * Dt) + G_1 * accAngle$$

where $Angle_{n+1}$: current angle,
$Angle_n$: last calculated angle,
gyroRate: rotation rate of gyroscope,
Dt: period of sampling signal,
accAngle: angle calculated from accelerometer,
G1: transfer function of low-pass filter, in range [0, 1]
1-G1: transfer function of high-pass filter.

The value of G_1 decides the system response time and the effect of filtering. A large value of G_1 means a fast response system and the low effect of filtering, vice versa. Therefore, the value of G_1 should be set according to the real situation and the testing.

This method can be used for the integration of the angles of tilt in XY- and XZ-planes from accelerometer (corresponding to θ and ψ in section 4.2.1.1) and the rotation rates of gyroscope on the responding directions. The angle towards the gravity ϕ which is the angle deciding the reference force can be calculated based on the output angles of the integration.

4.2.2 Tendon Load Cells

Tendon load cells (TLCs) are the sensors used to measure the forces. A TLC is applied with two connected ropes, which is attached between an actuator and the arm that should be assisted. Two TLCs are required to measure the forces, one measures the force of tendon near arm and the other one measures the force of tendon near the actuator. The force of tendon near the arm is provided as the feedback of the control unit to control the actuator. Moreover, we can obtain the force loss by comparing the difference between the force of tendon near arm and actuator. Following is the formula:

$$F_{loss} = F_{actuator} - F_{armpiece}$$

4.3 Force Control for Arm Support

Force control technology is implemented to pursue an accuracy controlling of the system. A traditional type of PID controller is selected to control the system.

4.3.1 Force Control

Force control [7] is a technology that has been developed to fill a void in the automated manufacturing process. Force control can be distinguished in two types: active and passive. Passive force control method is an open loop control system which does not consider a force feedback and has no contribute to adjust the force errors. Active force control method is a closed loop system which can automatically adjust to reduce force errors according to the feedback of force sensors. This project implements a active force control method using the feedback values from a Tendon Load Cell.

4.3.2 PID Controller

The PID controller, which consists of proportional, integral, derivative elements, is a control loop feedback mechanism widely used in industrial control systems [18]. This technology is well-developed, easy to implement and has good controlling effect. Figure 4.7 shows a general PID controller:

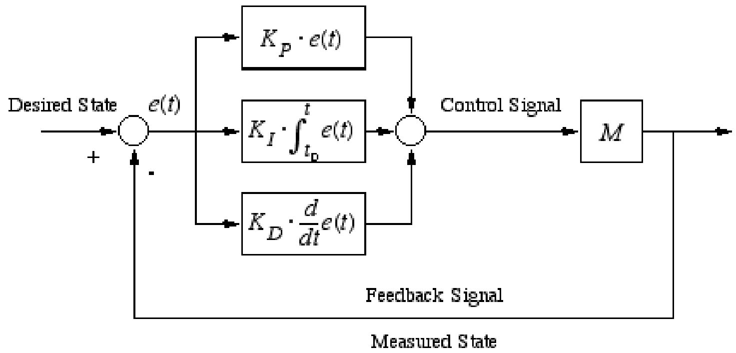

Figure 4.7: A general proportional-integral-derivative (PID) controller [9]

Ideally, the relationship between PID output u(t) and the error e(t) (Difference between PID input and feedback) can be shown as:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\mathrm{d}t + K_d \frac{\mathrm{d}e(t)}{\mathrm{d}t}$$

where K_p: Proportional gain,
K_i: Integration gain,
K_d: Differential gain,
t: time.

Discrete the algorithm, we can obtain the following formula to be implemented in computer:

$$u(k) = K_p e(k) + K_i \sum_{j=0}^{k} e(j) + K_d[e(k) - e(k-1)]$$

where k is the sampling instant.

The PID controller can be applied for the force control of the system. The input of the PID controller comes from the required force, and the actual force detected by the TLC performs as the feedback signal of the controller. The outputs of the controller are converted to electronic signals which drive the actuating mechanism.

Chapter 5

Design of the Arm-Assistive Device

This chapter describes the design of the arm-assistive device based on the system requirements. It indicates the overview of the whole system as well as the details of each subsystem, including the sensing unit, control unit, actuating unit and control panel. Moreover, it presents the structure of each subsystem and the interfaces between each components.

5.1 System Requirements

Identifying the requirements of the system is necessary to implement a good product. This thesis focuses on the requirements analysis of the electronic system.

As the system is defined to be a device assisting user's arm rather than replacing the functions of the arm, the requirements of system can be described as detecting user's intention and providing the support based on user's motion. Therefore, the system is required to analyse user's intention and transfer the needs to the reference force. Furthermore, the system should not only help with lifting user's arm, but also releasing the arm easily. The actuator should be safe, and response fast and accuracy. Moreover, the system should be suitable for different size of people, in other words, the supporting force should be adjustable and easy to modify. In addition, a control system is required to make sure the stability of the system. Finally, some buttons are needed for the basic operations, such as start or stop.

To implement the system, sensors can be applied to detect user's intention. As the sensors should be placed on user's arm, they should be small and lightweight. The sensors should also has high quality to obtain accurate data. Then the detecting signal should be transferred to the required force which can be implemented by software applied in the main board. The supporting force can be provided through a actuator installed on the back of the user. Moreover, the controlling of the system can also be implemented by software with the support of the feedback data from the sensors.

The interfaces between each component are important for the design of the system. The most important requirement could be stable. The transmission of the data between the subsystems should be stable and fast. The interfaces could also be CPU effective which means it is better to choose easy-to-implement interfaces with simple protocol. Moreover, the user interfaces should be clear and easy to use since the potential customers of the product are elderly people with disabilities.

5.2 System Architecture

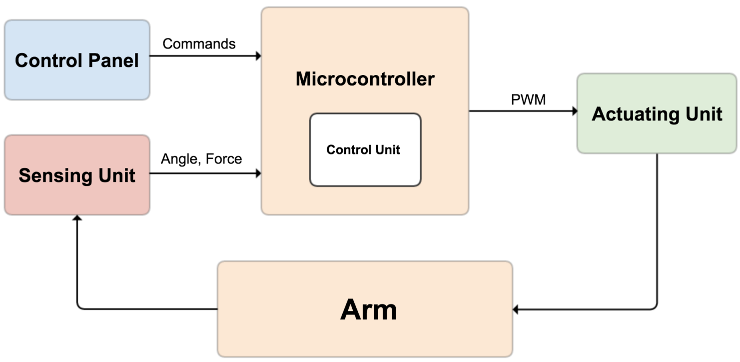

Figure 5.1: General Description of System Architecture

According to the system requirements, the system can be designed as four modules: sensing unit, microcontroller including the control unit, actuating unit and control panel. Figure 5.1 shows the architecture of the system. First, the control panel is designed as the user interface which user can send the commands, such as start or stop to control the system. The user can also adjust the support force through the control panel. Second, the sensing unit is designed to detect user's intention and the position of user's arm, and transfer the signals to the mirocontroller. Another function of the sensing unit is to measure the actual force in the tendon near the arm, which acts as the feedback of the control unit. Third, the microcontroller is the brain of the whole system, including the control unit. It receives the signals of angle and force from the sensing unit and generates the PWM signal to drive the actuator based on the output of the control unit. Finally, the actuating unit is implemented to drive the tendon which provides the force to lift the arm.

5.3 Sensing Unit

The sensing unit consists of an inertial measurement unit (IMU) and a tendon load cell (TLC). Figure 5.2 shows the structure and interfaces of the sensing unit.

There are three sensors available in a IMU, which are accelerometer, gyroscope and magnetometer. In this thesis work, only accelerometer and gyroscope are required. They can be used to detect user's intention and the position of user's arm in real time. There are several communication methods can be used to communicate between the accelerometer or the gyroscope and the microcontroller, such as I2C and SPI. I2C has been selected as the interface because it just need 2 connection cables, it has high communication speed and it is easy to be implemented. The TLC is a type of force sensor which monitors the force of tendon near the arm. The output signal of the TLC is in millivolt unit which is too small for microcontroller to detect, therefore, an amplifier is necessary to enlarge the signal. As the output of the amplifier circuit is analog signal, an analog-to-digital converter (ADC) could be enabled in the microcontroller to convert the signal from analog to digital signal.

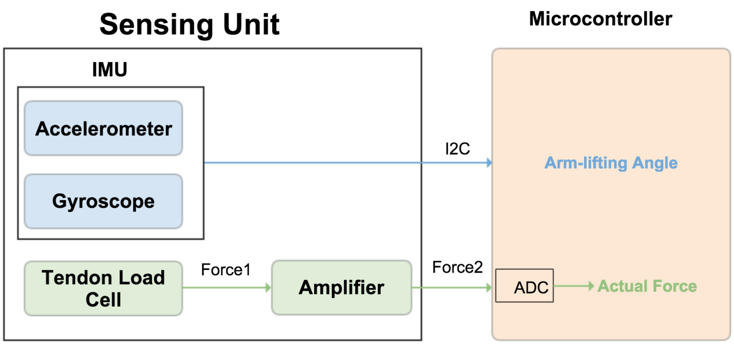

Figure 5.2: Structure and Interfaces of the Sensing Unit

5.4 Control Unit

The microcontroller is the key component of the system, it receives the signals from the sensing unit and generates the electronic signal to control and drive the actuator. Figure 5.3 shows the functions of the control unit.

When the microcontroller receives the position of the arm from the sensing unit, it transfers the position to the required force which acts as the reference input of the control unit. The actual force received from the sensing unit works as the feedback of the control unit. The controlling of the system can be implemented by using an PID controller which controls the actuator to provide enough force to follow the reference force. The output of the PID controller can be provided directly as the voltage signal to drive the actuator. However, the signal is noisy and needs high-level power supply. Nevertheless, the Pulse Width Modulation method could solve the problems as it has the advantage of reliable, power-effective and anti-disturbance ability. The input signal of the actuator can be PWM wave which generated by the microcontroller, and the output of the PID controller can be transferred to duty cycle of the PWM wave to control the speed and direction of the actuator. In addition, the position of the actuator is provided as the input of the position control to make sure the safety of the actuator.

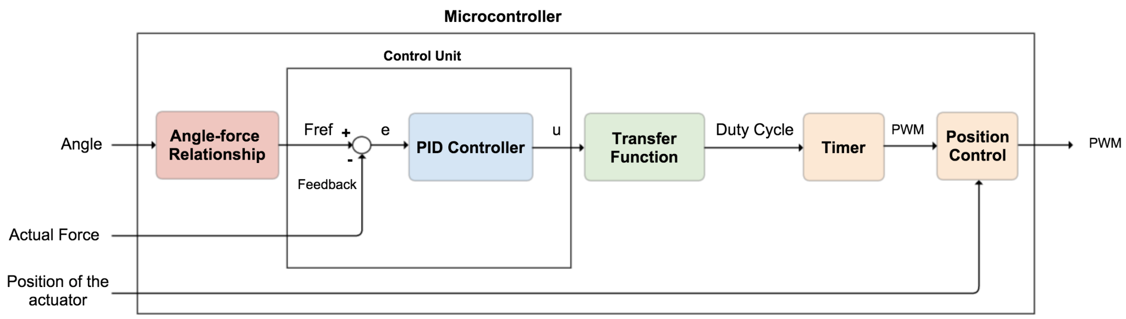

Figure 5.3: Functions of Control Unit

5.5 Actuating Unit

The actuating unit consists of a motor controller, a motor, actuating mechanism and a position sensor. Figure 5.4 shows the structure and interfaces of the actuating unit.

The motor controller is designed to govern the performance of the electric motor, and it generates the PWM signal to control the motor. There are many methods for the motor controller to receive the input, such as USB, logic-level (TTL) serial interface, analog voltage interface and PWM wave. In this thesis work, PWM mode is designed as the communication method between the microcontroller and the motor controller as it is power-effective and easy to implement. Moreover, the motor drives the actuating mechanism which pulls or releases the tendon connected to the arm, so that it completes the lifting and release of the arm. Additionally, a position sensor is installed to monitor the position of the actuator, and an analog-to-digital converter (ADC) should be applied in the microcontroller to convert the signal.

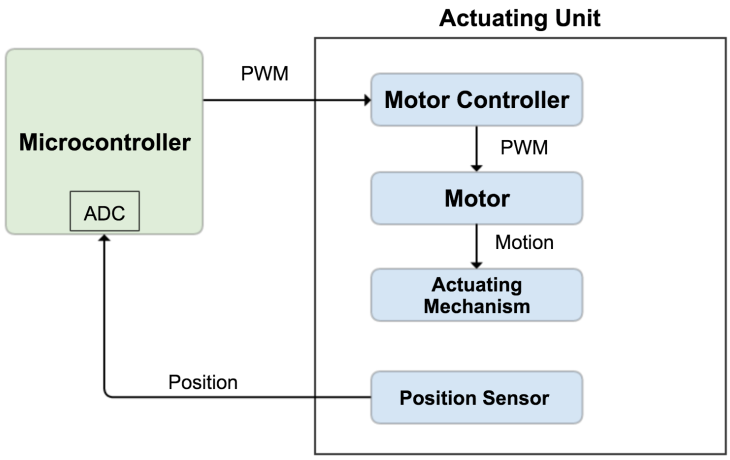

Figure 5.4: Structure and Interfaces of Actuating Unit

5.6 Control Panel

The control panel consists of four buttons, which are start, reset, release and stop, as well as a potentiometer. Figure 5.5 shows the structure and interfaces of the control panel.

The start and reset buttons are designed to execute some basic functions, which are starting or resetting the system. The release button is designed to release the arm if the system stops when user's arm is lifted. The general purpose input output (GPIO) technique could be implemented in microcontroller to receive the signals from the three buttons. Furthermore, the stop button is used to power off the system at the emergency situation. Additionally, a potentiometer is designed to adjust the maximum value of the reference force to fulfill the different demands of different size of people. An analog-to-digital converter (ADC) could be enabled to convert the signal from the potentiometer.

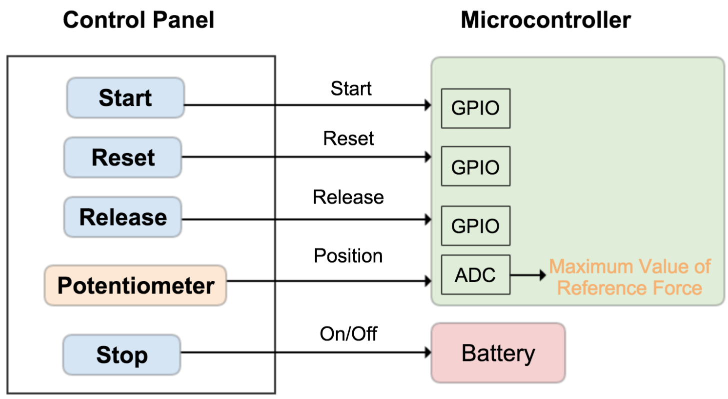

Figure 5.5: Structure and Interfaces of Control Panel

Chapter 6

A Prototype of the Arm-Assistive Device

This chapter describes the final implementation of the electronics and software system of an Arm-Assistive device. It indicates the types, electronic characterises and functions of the selected components as well as the application method of the components. The installation and location of each component are described in details. The integration of the system is also presented in this chapter. The system was implemented using Commercial off-the-shelf (CTOS) technology, with the ready-made microcontroller, breakout boards and sensors. Based on the system design, a complete description of the system architecture is shown in Figure 6.1.

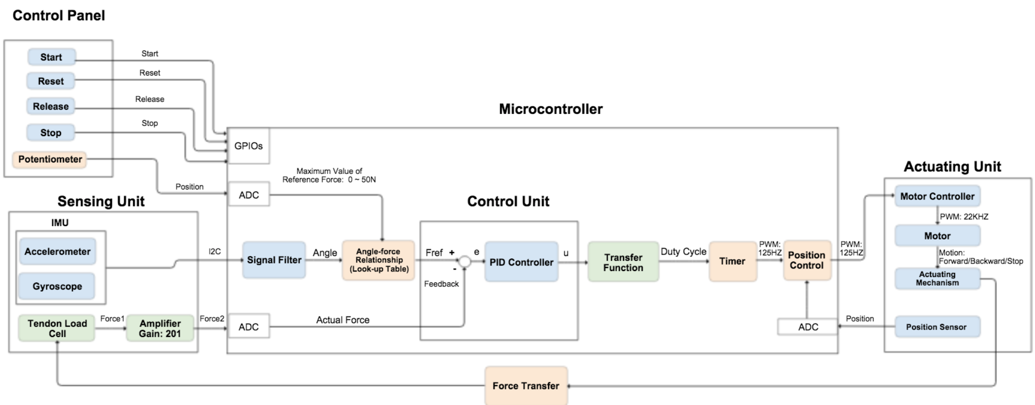

Figure 6.1: Complete description of System Architecture

6.1 Sensing Unit Implementation

The sensing unit consists of an inertial measurement unit (IMU) and a tendon load cell (TLC). The IMU is located on user's upper-arm and measures user's intention and the position of user's arm. The TLC is installed close to user's arm and detects the force on the tendon. Shown in Figure 6.2.

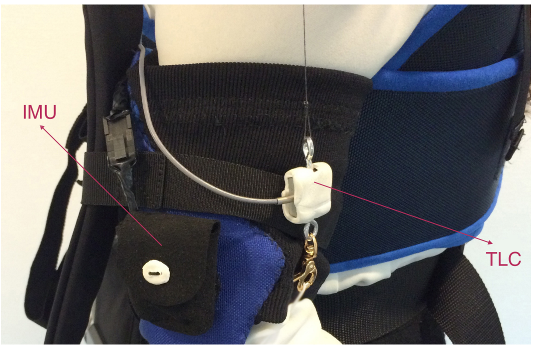

Figure 6.2: Sensing Unit Implementation

6.1.1 IMU

In order to obtain the position of the arm, we applied a micro-electro-mechanical systems (MEMS) technology based IMU which is located on the arm piece. Shown in Figure 6.3.

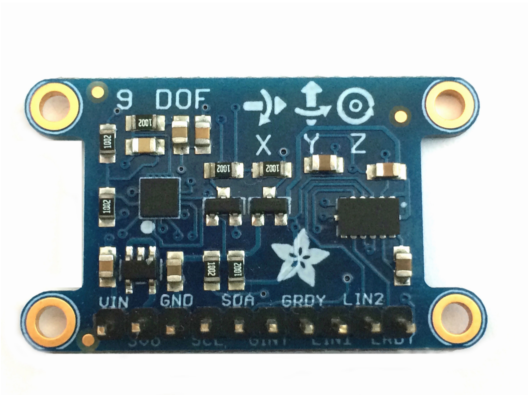

Figure 6.3: 9-DOF IMU Breakout Board [1]

This IMU breakout board consists of two main chips. First, LSM303DLHC, which is a compact sensor featuring a 3D digital linear acceleration sensor and a 3D digital magnetic sensor. Second, L3GD20, which is a low-power gyroscope with three-axis digital output. The accelerometer and gyroscope are combined to detect the user's intention and the results from the sensors are used to calculate the lifting angle of user's arm based on the discussion on Chapter 4.2.1.

This IMU breakout board can be powered by 5 Voltages, and all the sensors share a I2C serial bus interface which can be used to communicate with the main board. The I2C communication library of STM32F401 board has been used to implement the software driver of the sensors.

6.1.2 Tendon Load Cells

In order to implement a stable system with accuracy control, it is necessary to pay attention to the actual force on the tendon. The actual force can be provided as the feedback of the control unit to form a close-loop control system which is more stable than an open-loop system. The force on the tendon lose on the way passing from actuator to the arm, therefore, detecting the force on the tendon near the arm piece provides a more meaningful value. Moreover, the force can be detected by a tendon load cell. There are a variety types of tendon load cells (TLCs) in the market, type SMTM Micro S-Type Load Cell by Interface has been selected as it is lightweight and has high resolution with the output in mV scale. It has a sensitivity of 2.359mV/V and a measurable range from 0 to 100 Newton. Shown in Figure 6.4.

Figure 6.4: SMTM Micro S-Type Load Cell [12]

As the output of the TLC is in mV unit which is too small for detection, an amplifier is needed to enlarge the signal of the output. The gain of the amplifier has been decided to be 201 as the maximum value of the Analog-to-Digital Converter (ADC) input is 3 Volts. Hence, the force measuring from the tendon load cell after the amplification is calculated as:

$$Force = \frac{Voltage}{Gain * Vdd * Sensitivity}$$

where Voltage: amplified voltage reading,
Gain: gain of the amplifier, 201,
Vdd: power supply voltage,
Sensitivity: sensitivity of the TLC, 2.359mV/V.

6.2 Control Unit Implementation

The control unit has been implemented using a traditional type PID controller based on the discussions in Section 4.3. However, there are many situation should be consider during the implementation. For example, a threshold of error is necessary that the PID will not response to the error which is smaller than the threshold. When the error has been adjusted into a system acceptable range, the output can be set to zero, which eliminates the floating of the movement at the stable state. It is also necessary to set the limitation of the output and the integral part of PID controller, as they could be increased to infinite and exceed the range of the system. Listing 6.1 is the pseudo code of the PID controller.

Listing 6.1: pseudo code of the PID controller.

```
previous_error = 0
integral = 0
loop:
  error = desired_value − measured_value
  integral = integral + error
  derivative = error − previous_error
  /*Threshold control: do not adjust system when error is smaller than
  error_min*/
  if error > error_min
    output = Kp*error + Ki*integral + Kd*derivative
  else
    output = 0 //save power and prevent floating movement
  /*Threshold control of output*/
  if output > output_MAX
    output = output_MAX
  /*Threshold control of integral part*/
  if integral > integral_MAX
    integral = integral_MAX
  previous_error = error
```

6.3 Actuating Unit Implementation

The actuating unit receives the PWM signals (125HZ, 5 Volts) from the stm32f401 board and provides the corresponding force to support user's arm. The motor rotates at a certain speed according to the duty cycle of the PWM wave and drives the actuator to pull the tendon which lifts user's arm. In addition, a position sensor is implemented to detect the position of the actuator which provides the information to make sure the actuator stops when it moves to the end. Figure 6.5 shows the architecture of the actuating unit.

6.3.1 Motor

Motor is an important part of the actuating unit, it decides the speed and electrical characteristics of the actuator. To implement a high quality actuator, we chose a DC motor from Maxon, type RE 25, Graphite Brushes, 20 Watt. It has a nominal voltage of 12 Volts, and it can run continuously at maximum current of 2.25 A. Furthermore, It can operate at a high speed which reaches 8630 RPM.

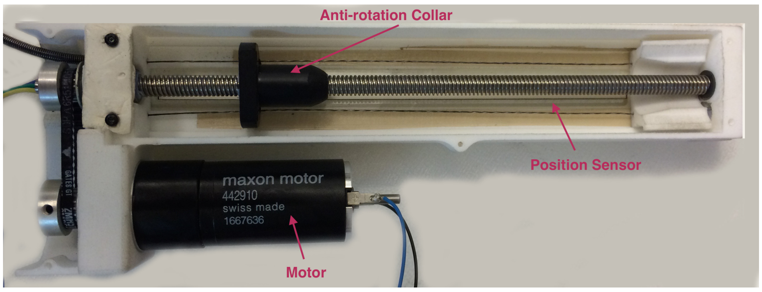

Figure 6.5: Linear Actuator

6.3.2 Motor Controller

A controller is required to control the motor. It transfers the signal received from STM32F401 board to the PWM signal which controls the motor. To select the suitable motor controller, the power supply of the motor, size of the controller and the controlling method are taken into account. A simple motor controller 18V7 from Pololu (shown in Figure 6.6) is chosen to control the actuator. It provides bidirectional control of one DC brush motor with a voltage range from 5.5V to 30V. It can run continuously at 7A as the maximum current output. To receive the input signal from the stm32f401 board, radio control (RC) pulse width interface is configured as the input method. The motor controller generates PWM waves with different duty cycles according to the width of the received pulses which controls the motor.

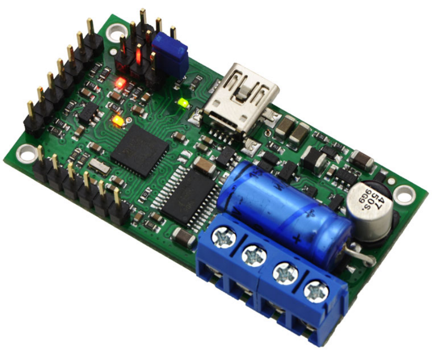

Figure 6.6: Pololu Simple Motor Controller 18v7 [23]

6.3.3 Position Detection

Since there is a limited length of the actuator, the motor must stop when the anti-rotation collar moves to the beginning or the end position. Therefore, a stop function is required to make sure the safety of the actuator. SoftPot Membrane Potentiometer - 50mm is selected to implement the stop function. The position sensor always measures the position of the force pressed on it, therefore, we installed it under the anti-rotation collar of the actuator to obtain the position of the anti-rotation collar. The algorithm has been implemented in the main board that whenever the anti-rotation collar moves to the beginning or the end, the motor stops, which makes sure the safety. However, when an error occurs, for example the anti-rotation collar is not pressing on the position sensor, the value reading from the position sensor could be wrong which increases the risk of the safety. In order to solve the problem, a pull down resistor (shown in Figure 6.7.) could be added between the output pin and the ground of the position sensor. When the sensor is floating or the value reading from the sensor is wrong, the output of the circuit will always be low, then the motor will stop which guarantees the safety.

Figure 6.7: Position Sensor from Spectrasymbol [28]

6.4 Control Panel

The control panel works as the user interface which operates some basic functions, such as start or stop, shown in Figure 6.8. There are four buttons and one potentiometer on the control panel. The three black buttons have the functions of start (user button), go-down(release button) and reset (reset button). The user button is used for starting of the system; the release button is implemented for the situation that the system stops when user's arm is lifting; and the reset button is for resetting the system. The red button is the stop button which cuts the power at the emergency situation.

The potentiometer (type B100K) is used for setting the force for people with different demands, and it has a range from 0 to 50 N.

Figure 6.8: Control Panel

6.5 Integration of the Components

The whole system consists of vest, shoulder padding, arm piece, actuator, electronic box, IMU, TLC, control panel and battery. The system works as the following process: at the beginning, open the stop button and press the start button on the control panel to start; then the user can lift the arm up, and the IMU detects the angle of the arm and compares with the force from the TLC in the PID controller; after that, stm32f401 board generates the PWM wave based on the output of PID controller and sends it to motor controller; finally, the actuator drives the tendon to support the arm and the speed of the actuator is obtained based on the converted value of the duty cycle of the PWM wave. To release the supported force on the arm and let the arm go down, the user should relax the arm which increases the force of the TLC, and the PID controller will do the calculation and generates a negative output and send the value to actuator to release the arm.

Chapter 7

Evaluation

This chapter describes the evaluation process and results of the electronic and software system of the device, including the technique evaluation of the components and a user test. The technique assessment shows the performance of the sensors and the algorithms. The user test was organised in a research center and indicates the viability of the approach.

7.1 Evaluation Setup

The evaluation was performed to assess the assisting effect of the prototype. First, we need to know the functionality of each components, including the accuracy of the sensor, the response speed of the controller and the effect of the signal filter. Second, the performance of the whole system is an important item for the evaluation. We need to integrate all the components and test the whole system to know whether the system can perform all the functions and fulfill the requirements. Finally, the system should be assessed by the potential customers to identify the details of the functionality of the product as well as the strengths and weaknesses of the product.

The system was tested on a model as well as real person. It was also tested on the potential group of user. The components of the system has been evaluated individually before the integration.

The system was evaluated by a visualised monitoring tool built in LabVIEW in PC. LabVIEW [17] (short for Laboratory Virtual Instrument Engineering Workbench) is a system-design software providing the development environment for measurement or control applications from National Instruments. The stm32f401 board was configured to transfer and receive the data through user USB port. The system has been monitored by receiving the data from the virtual serial port in PC. See details in appendix A.

For the user testing, the evaluation has been organised by putting the device on the tester and asking the tester to perform some movements, such as lifting the arm and pretending to eat. The related parameters, such as position of the arm, reference force and measured force have been monitored and recorded by LabVIEW for further analysis. Moreover, each tester received an interview after the evaluation about the comfortable, force support level of the device, etc.

7.2 Results

This section shows the processes and results of the evaluations, including the technique evaluation of each components and the interview of the testers. First, we tested all the sensors and evaluated the performance of the IMU sensor and the signal filter to identify the accuracy of the sensing data and the filtering effect. Then, we tested the device on people and adjusted the angle-force relationship according to the opinions of the testers. The performance of the control unit is also needed to be assessed which decides the stability of the system. We evaluated the response speed as well as the stability of the system and decided the parameters of the controller according to the result of the evaluation. Moreover, the device was tested on a potential group of user to identify the strength and weakness of the product.

7.2.1 Evaluation of IMU

The performance of the IMU decides the accuracy of the sensing data which is very important. In order to evaluate the performance of the IMU and the complementary filter, we asked the tester to abduct the arm from 0 to 90 degrees. The movement consumes about 1 second. Figure 7.1 shows the difference between the angle calculated by accelerometer alone and the filtered data from the combination of accelerometer and gyroscope.

According to Figure 7.1, we can see the angle calculated by raw data increased from 0 to 90 degrees starting from sampling point 100 to point 280, while the angle calculated by the filtered data increased to 90 degrees until sampling point 375. The correct increasing of the angle from 0 to 90 degrees shows the correctness of the position detection of IMU and the algorithms of angle calculation in abduction DOF. The delay of the filtered signal shows the functionality of the complementary filter, it only response to the long-time changes of the accelerometer. The response time can be changed by adjusting the transfer function of the complementary filter.

Another test of the IMU and the filter has been implemented by moving

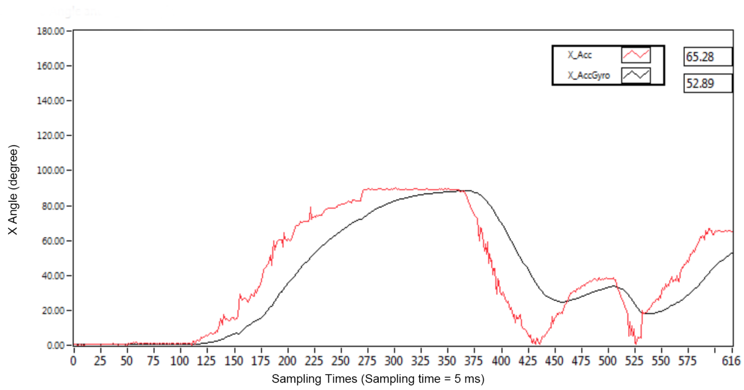

Figure 7.1: Comparison of the raw data and the filtered data by lifting the arm from 0 degree to 90 degrees.

the IMU slowly to an angle and adding the noise by typing the IMU board very fast. Figure 7.2 shows the result of the test.

As we can see from Figure 7.2, the raw data responses to the noise immediately which is not available to be used in the system. Nevertheless, the filtered data is stable and has a smoothly movement which means the complementary filter has a good performance of avoiding mechanical noise and the output from the filter is safe to use.

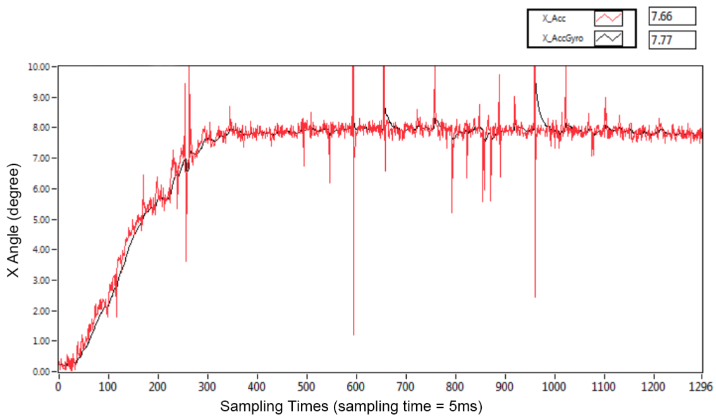

Figure 7.2: Raw accelerometer data vs. Filtered accelerometer and gyroscope data

The similar evaluations was applied in flexion and other directions, and we obtained all positive results.

7.2.2 Angle - Force Relationship Test

The transfer from the angle to reference force has been implemented using look-up table. The look-up table was built based on the theory discussed in Section 4.2. The evaluation has been implemented first on a human model with a wooden arm and then tested on the real person for better understanding.

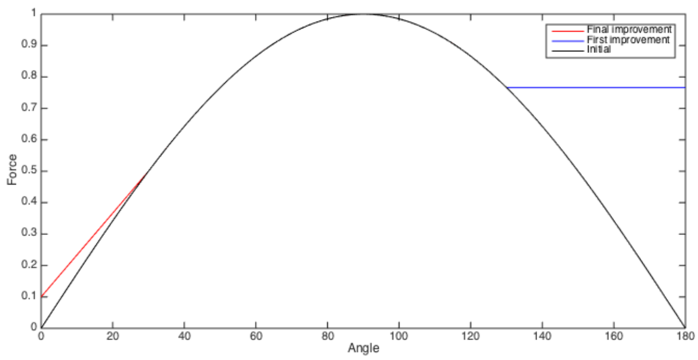

Figure 7.3: Angle-Force relationship

First, we programed the system to lift the wooden arm of the model slowly and recorded the relationship between the angle lifted and the force on the tendon near the arm. However, the result of the test was not satisfied, because there were much force loss due to the friction between the wooden arm and the body when lifting the arm. Then we determined to evaluate it on real people instead of the human model. We implemented the sine wave for the angle-force relationship (shown in Figure 7.3: Initial) and applied the tests on different size of people. Most of the testers said they were satisfied with the support when lifting the arm from 0 to 90 degrees. However, they did not feel enough support when elevating the arm over 130 degrees. The result shows that more force should be provided over 130 degrees and the reason might be the user need to hold the arm over 130 degrees to do some operations, such as eating or drinking which takes time and needs more force support. Therefore, we changed the force to a constant value over 130 degrees (shown in Figure 7.3: First improvement) and we received a positive result from the testers. They said they felt enough supports and the movements were comfortable.

However, another problem was found during the tests. There were delays at the beginning when lifting the arm which made the system slow. We observed the movements of lifting and dropping, and found that the tendon loose every time when the arm went down to 0 degree. Therefore, the tendon should be tighten up again when lifting the arm next time which caused the delay. The problem was solved by increasing the force at the beginning, from 0 to 30 degrees (shown in Figure 7.3: Final improvement).

The final implement of the angle - force relationship is shown in Figure 7.4.

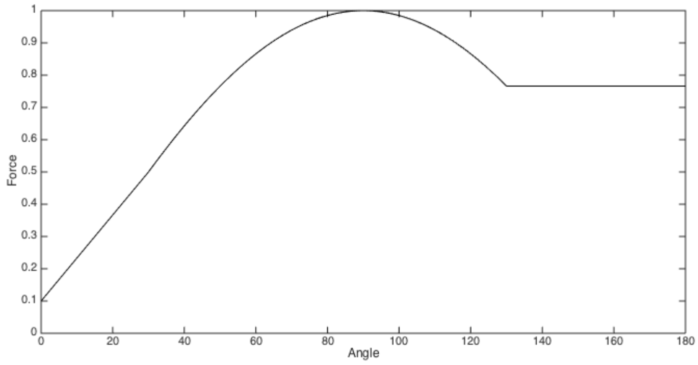

Figure 7.4: Angle-Force relationship

7.2.3 PID Controller

PID controller is an important component of the system. It decides the response speed and the stability of the system. Tuning the parameters of the PID controller was difficult and took much time, but the PID controller has excellent performance on controlling the system.

We evaluated the PID controller by applying the step signal and sine signal on the system, and recorded the result separately. According to Figure 7.5, we can see the response time of the system for the step signal was about 125 ms which was fast and met the requirements. Moreover, the actual force increased to the reference force correctly when the reference force jumped to 15N at sampling time 200, and the system was keeping stable after the disturbance. Furthermore, when the reference force increased again to 30N at sampling time 410, the system was fitted to the change quickly and kept the system stable again.

In order to have a better understanding of the performance of the PID controller, another test was implemented with the movement of sine wave. The system was programed to move following a sine wave with the period of 6 seconds. According to Figure 7.6, we can see the actual force followed

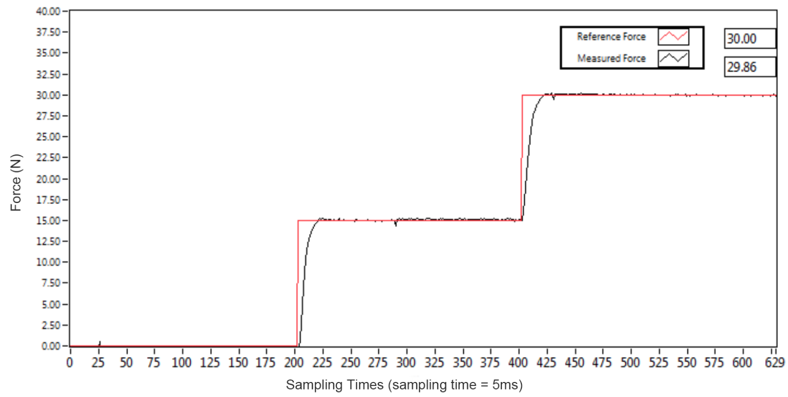

Figure 7.5: The step response of the PID control system

the reference force correctly when it entered the control state after sampling time 600. There were some errors every time after the direction change which were caused by friction. Nevertheless, the errors were small that could not affect the performance of the system and the system was still stable when the errors happen.

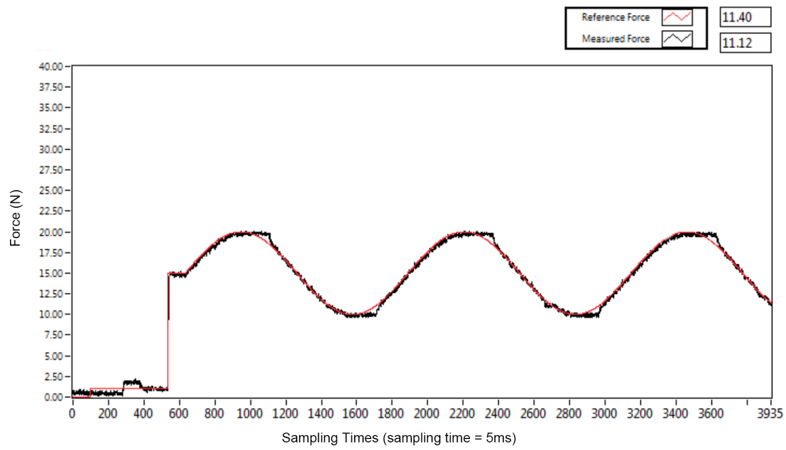

Figure 7.6: The sine response of the PID control system

7.2.4 User Test

The feedback from the potential user is good for research and product development. Therefore, the user test is necessary to identify the functionality of the product as well as the strengths and weaknesses of the product. An user test was organised in a research center and indicates the assisting effect of the device. An safety test has been applied before the testing on users. Then the device has been put on the user and check whether the device can help the user or not. The users are the people with reduced force strength on the arm and they have a very limited range of moving the arm. The result shows that the device can help the user lifting the arm as well as do some basic operations, such as eating or drinking. The testers are satisfied with the functionality of the prototype and showed great interest in the product.

7.3 Discussion

In this thesis work, we successfully implemented a soft robotics solution which provides extra strength to the arm function of the elderly users. The product fulfills the safety requirements and is easy to use. It can be controlled by the user himself and can be adjusted according to different needs of users.

The prototype of the solution used commercial off-the-shelf technology which reduced the development time and decreased the cost of the components. The result of using soft robotics technology shows an advantage of comfort, wearable and lightweight of the product. Therefore, the wearable soft robotics technology could be applied in arm-assistive medical devices and has an excellent effect.

Although the prototype of the product can perform some basic operations, there are still many places need to be improved for further development. Here, we discuss the improvements can be implemented for the electronic system.

The accelerometer and gyroscope have been combined for more accuracy of the sensing, a magnetometer can be added to improve the calculation of the arm position which improves the user intention detection. Data fusion can also be improved by applying an advanced filter which can contribute to the result of the sensing unit, including the arm position and the measured force.

The function of recording user's activities can be implemented on the device by using the Wifi or bluetooth communication technology. The device can be connected with the cloud server to store the data for further analysis, such as the evaluation of user's health. Furthermore, a remote control function can also be implemented that the user can control the device by himself and adjust the demanded force easily.

The control algorithm used for now is the traditional type of PID controller, applying an advanced controlling algorithm can increase the stability and speed of the system. Moreover, implementing the sensors on the end of the actuator to detect the position of the actuator can improve the safety and risk of the system. The noise of the actuator and the power consuming problem should also be improved.

The existing device provides the support only according to the angle between the upper arm and the body of user, analysing the movements of the lower arm provides a better understanding of the force requirements. Another function can be considered is to provide the force support of the lower arm by detecting the angle of elbow.

As there is a trend to improve the wearable devices lightweight and comfortable, the size of the electronic system and the actuator could be considered. The sensing unit can be designed to be smaller and integrated into the fabric of the arm-piece.

Chapter 8

Conclusions

As many elderly people are suffering from a problem of shoulder and arm, such as stroke and frozen shoulder, or the pain in the arm when reaching high, it is necessary to develop a medical device to help them with the movement of the arm. The research shows most of the assisting device in the market or in study are heavy and expensive, some of them cannot work autonomously, which should be installed on the table or wheelchair. Therefore, the developing device should be lightweight, cost-effective and wearable.

According to the discussion in the previous chapters, we can draw the conclusion that wearable technology and soft robotics technology can be used to implement a device helping people lifting the arm. Such a device can be implemented by detecting the intention of user's movement and transferring it to force signal, and then providing the required force.

The device has been designed as four modules, including the sensing unit, control unit, actuating unit and control panel. The sensing unit is designed to detect user's intention and the position of user's arm as well as measuring the actual force in the tendon near the arm, which acts as the feedback of the control unit. The control unit controls the system and generates the electronic signal to drive the actuator. The actuating unit is implemented to drive the tendon which provides the force to lift the arm. The control panel is designed as the user interface for starting or stopping the system as well as adjusting the support force.

The evaluation of the system shows a satisfied result with the respect from both the technology and the user experience. Instead of using rigid materials, we used soft materials and organic structures to implement the arm-assistive device, which makes the device lightweight, cost-effective and comfortable. The device is also wearable and can work autonomously which is an advantage over the other products. The work could be continued by adding the force support for the lower-arm as well as improving the sensing technology. Additionally, with the developing of the device, I believe it can help all the elderly people with the arm problem and most of them can enjoy a better personal life.

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Appendix A

First appendix

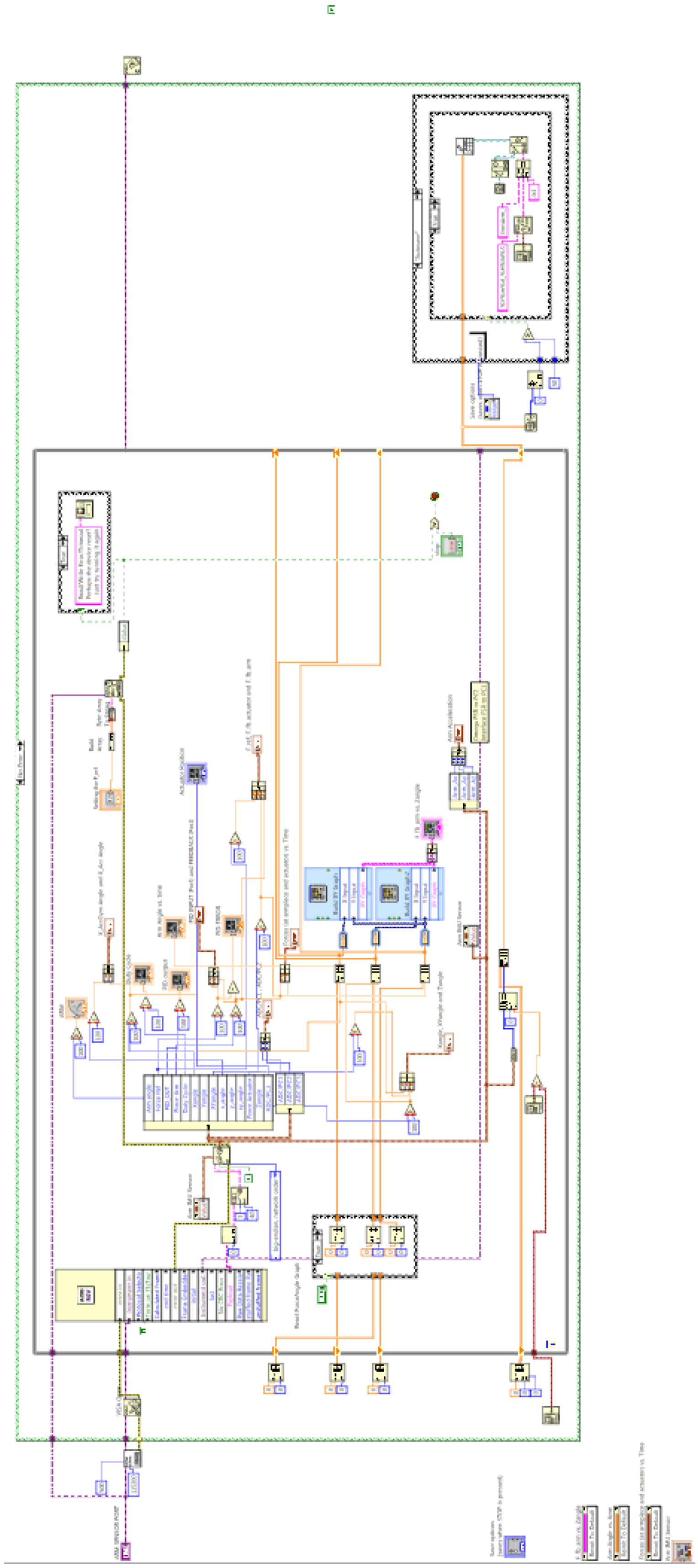

Figure A.1: LabVIEW Setup